

Island Elevations, Reef Condition and Sea Level Rise in Atolls of Chagos, British Indian Ocean Territory

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ABSTRACT

Three years after most corals died on the central Indian Ocean reefs of Chagos, mortality remains very high to 15 m deep in northern atolls, and to >35 m in central and southern atolls. Many shallow reef surfaces have 'dropped' 1.5 m due to loss of dense coral thickets of *Acropora palifera*, coral bioerosion is substantial, and there is much unconsolidated rubble. Juvenile corals are abundant, though mostly are found on eroding or unstable substrates. There is a 'race' between erosion and new growth, whose outcome is unknown at present.

Sea surface temperature (SST) has risen 0.65°C since 1950. In 1998, the critical SST causing mortality in these atolls was 29.9°C. Accompanying sea level rise in this region is predicted to be over 0.5 cm y^{-1} .

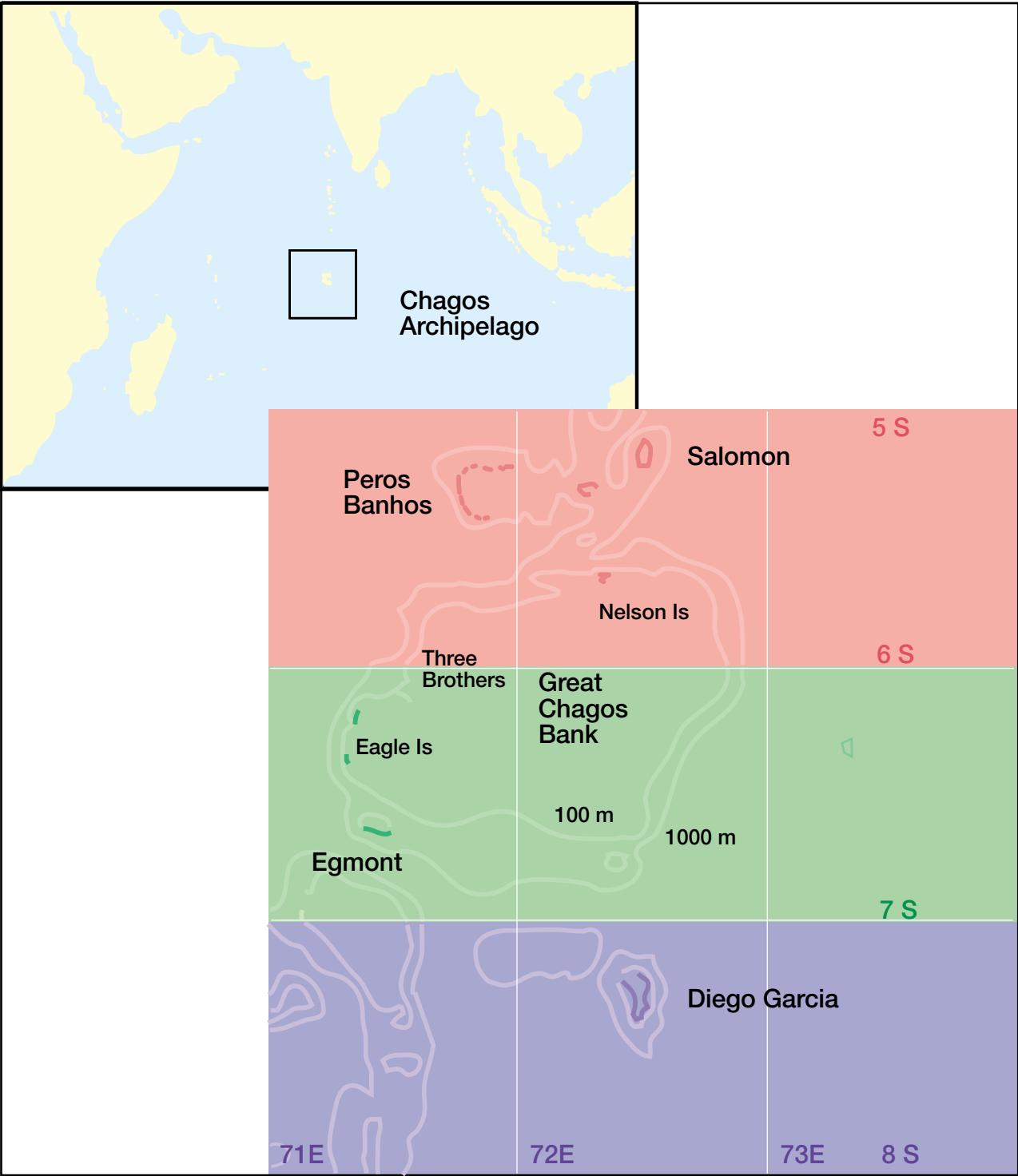
Profiles of several islands were surveyed over 25 years ago. Most islands have a raised perimeter surrounding a central depression located near or even below sea level. Protecting the islands from erosion are (or were) three 'lines of defence': firstly the now absent seaward coral thickets of *A. palifera*; secondly the *Porolithon* algal ridges at the seaward edge of the reef flats and, thirdly, wide expanses of reef flat located near present sea level, across which waves decay. Reduction in effectiveness of any of these will transfer wave energy inward to the shores and elevated rims of the islands. Consequences could include erosion or even breaching of island rims.

INTRODUCTION AND METHODS

Following the massive coral mortality in many Indian Ocean archipelagos in 1998 (McClanahan, 2000; Spencer *et al.*, 2000; Sheppard *et al.*, 2002), effort is being made to determine what consequences might arise which will affect local communities and shorelines. All three major functions of coral reefs, namely maintenance of diversity, productivity and coastal protection, are at risk from the mass mortality which has left many reefs markedly depleted. Much new coral recruitment has been observed (Turner *et al.*, 2000; Sheppard *et al.*, 2002) but it is uncertain what proportion of juveniles will survive the unstable substrates to reach maturity.

In the Chagos Archipelago (Fig. 1), air temperature patterns have risen about 1°C in 25 years (Sheppard, 1999a), with a corresponding reduction in cloud and an increase in wind variance. No sea temperature series were measured during that period, though recently, interpolated sea surface temperature (SST) data has become available (Sheppard & Rayner, 2002) whose patterns match closely those of actual air temperatures.

Figure 1. Location and map of Chagos Archipelago, and the grid of 9 one-degree cells for which sea surface temperature is available. Bathymetry lines are 200 and 1000 m depth. Colour coded blocks relate to figure 2.



It has been predicted that significant changes would take place to reefs in all affected areas of this ocean (Wilkinson, 2000). Many of the corals killed were hundreds of years old, and it was clear that, whether or not the cause is cyclical, natural, or even an isolated occurrence, an event of this magnitude has not occurred for several centuries or even millennia (Aronson *et al.*, 2000).

As well as having great intrinsic interest, the Chagos archipelago is an important stepping stone in East-West migrations of marine species across the Indian Ocean (Sheppard, 1999b). Belying the small area of its islands (4000 ha), reef habitat to 60 m depth exceeds ~13 000 km² (Dumbraveanu & Sheppard, 1999), giving it enormous biogeographical importance.

The responses of the coral reefs to the 1998 mortality is discussed elsewhere (Sheppard *et al.*, 2002). To date much less work has been done on the consequences of the coral mortality on the islands (in this or any other Indian Ocean archipelago), although the latter aspect is of major importance to island communities.

There are three main physical barriers to coral island erosion: the shallow part of the seaward reef slope, the reef crest, and the expansive reef flat. Abundant data on pre-1998 conditions exist for all three broad zones (e.g. Sheppard, 1980, 1981), but assessment of their condition post-1998 is so far limited to that on the first, namely reef slopes (Sheppard *et al.*, 2002). Regarding the second barrier to erosion, there has been, regrettably, no good quantification of calcareous algal cover on the reef crest, though it was observed (Sheppard, 1999c) that this was noticeably reduced compared with 20 years earlier.

Regarding the third barrier (the expansive reef flats and the shorelines of the islands themselves) two relevant sets of information are now available or have been rediscovered: first is predicted sea level rise based on climate models, and second is surveyor transect levels measured in the 1970s, across several islands, from seaward to lagoon shore. These were performed on Joint Services Expeditions to Egmont atoll (southern Chagos) in 1972/3 and to islands of the Great Chagos Bank in 1975. Traditional

methods of levelling using tapes and theodolites were performed along transects cut through vegetation to allow adequate lines of sight (Anon, 1973; Baldwin, 1975; and unpublished charts). These data are re-examined here in detail. The accuracy of the levels is not questioned, though the absolute elevations above a sea level datum was not fixed as accurately as would now be desirable. However, discussions with some of those who prepared the island profiles has meant that the levels redrawn here are considered most useful in the context of assessment of possible island erosion and inundation.

RESULTS

Surface Sea Water Temperature Changes

Fig. 2 shows mean SST in 9 cells of 1° latitude and longitude, centred on the Chagos archipelago. Mean SST rose over 50 years by nearly 0.7°C, or about one quarter of the magnitude of an annual cycle which is ~3°C. Air and SST track each other closely (Sheppard & Rayner, 2002); air temperature is cooler by 1–2°C, but is rising faster. The higher specific heat capacity of water explains this difference, but acceleration of SST rise seems possible.

Critical SST values for coral mortality vary according to region (NESDIS, 2001). In Chagos, 29.9°C is a key indicator of coral mortality, providing a useful index for prediction of future similar coral mortalities, though factors such as UV penetration are also important. Simple extrapolation of these data (not shown) suggests that the straight-line rise in April SST will reach this critical value in about 2020, and even mean annual SST will do so in 2030. Annual fluctuations above this 'lethal index' would be expected repeatedly well before then, and indeed nearly did so in April 2001 (NESDIS, 2001).

Sea Level Rise

Sea level (Fig. 3, page 206) is predicted to rise between about 5–20 cm by the year 2040 (IPCC, 2001). This rate equates to up to 0.5 cm per year, a value which is actually less than measured sea level rise in the nearby Maldives (Singh *et al.*, 2001) where values of between

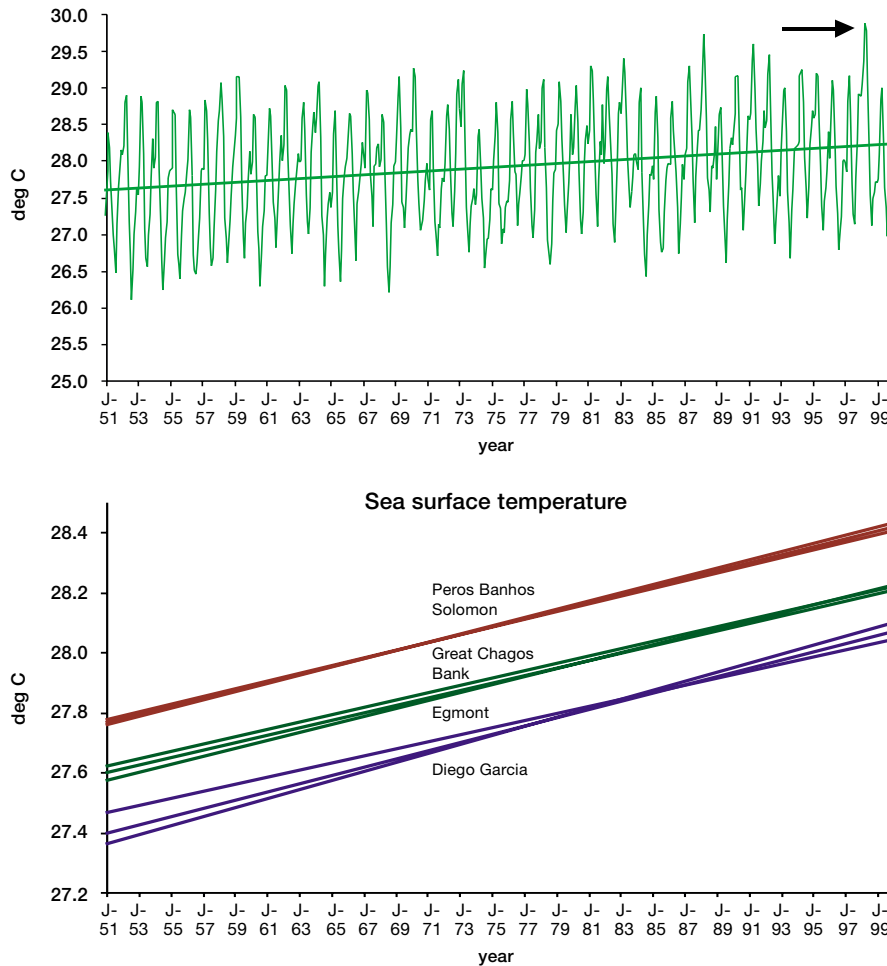


Figure 2. *Top:* Monthly mean sea temperatures of the middle row of latitude (including much of Great Chagos Bank and Egmont atoll whose islands are focussed upon here). Straight line is the simple regression line. Arrow marks the point which caused the 1998 mortality. *Bottom:* Lines of best fit for all 9 cells.

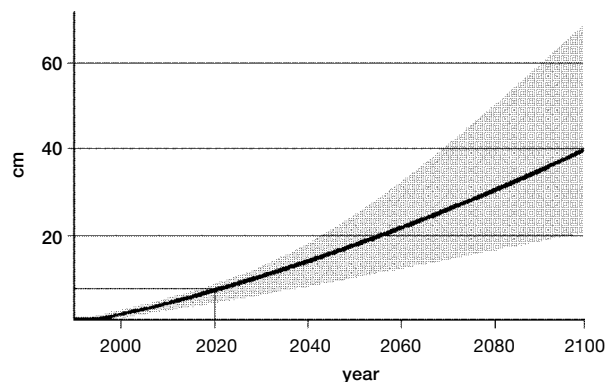
5.8 and 8.5 mm y^{-1} (depending on season) have been measured over the past few years. A short series of sea level data from the Chagos indicates a rise currently of 5.5 mm per year. IPCC (2001) predicts a likely acceleration in sea level rise as time passes.

Coral Erosion and Recruitment, Sand and Rubble

In shallow water, erosion of dead corals is marked. Where the large and robust *Acropora palifera* used to

dominate on seaward facing reefs, the killed colonies have been almost totally removed. Since these used to form a 1–2 m tall, impenetrable thicket to about 5 m deep, their removal has effectively lowered parts of these reef surfaces by about 1 to 2 m (Fig. 4 on next page). This is a region of great consequence to attenuation of wave energy, though erosion, rubble formation and mortality was recorded to depths considerably greater as well (Sheppard *et al.*, 2002).

Sea level rise



Sea level rise

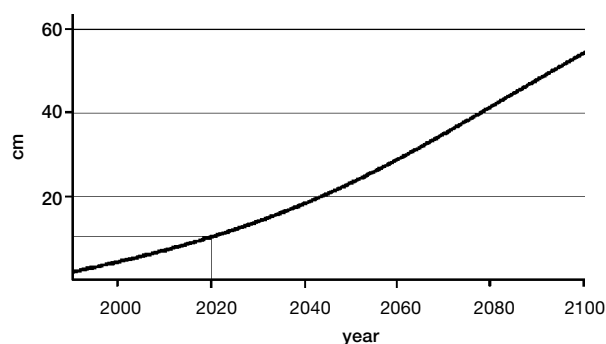


Figure 3. Sea level rise prediction (taken from IPCC, 2001).



Figure 4. A remnant of *Acropora palifera* on a seaward reef slope. The standing skeleton shows the depth to which substrate has been removed.

Rubble is extremely abundant and shows geographical patterns. The western edge of the Chagos Bank has smaller rubble, suggesting a more advanced state of erosion. Smaller rubble (more advanced erosion) also occurs in larger atolls. Of probable importance, but so far unmeasured here or elsewhere, is the fact that further erosion of rubble will create large quantities of sand. The importance of this here is the question whether this increased sand will assist maintenance of islands *via*

Egmont atoll

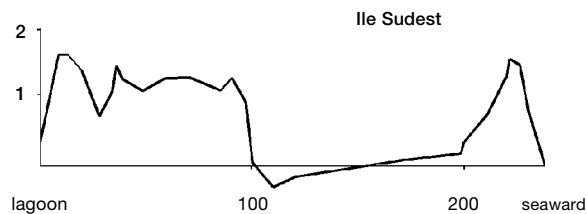
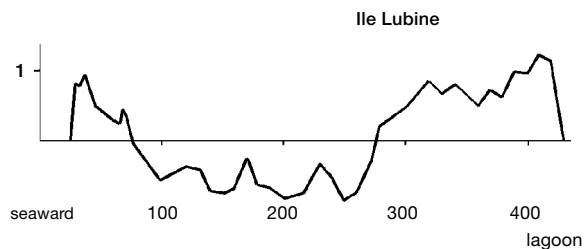
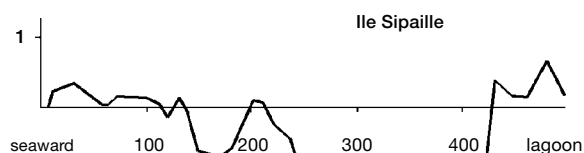


Figure 5. Profiles of islands of Egmont atoll drawn for survey transects carried out in 1972/3. Numbers are all metres. Redrawn from unpublished charts loaned from M. Hirons.

build-up of beaches. However, at some locations, chutes of scoured substrate indicate that much of this newly created rubble is being carried into deeper water.

Shores and Island Profiles

Fig. 5–7 show profiles of several islands, measured in the 1970s. Remarkably, most of them show elevated rims surrounding a depression which reaches to near sea level or even below it. It was noted that the absolute elevation

above a sea level datum was not accurately fixed, but discussion with the chief surveyors has allowed the x-axes of these profiles to be adjusted approximately to present high tide level. Spring tidal range here is approximately 1 m.

The central depressions of these islands are sometimes marked and are clearly obvious even on thickly vegetated islands. Formed possibly by solution by mildly acidic rain acting on the basic limestone rock, the de-

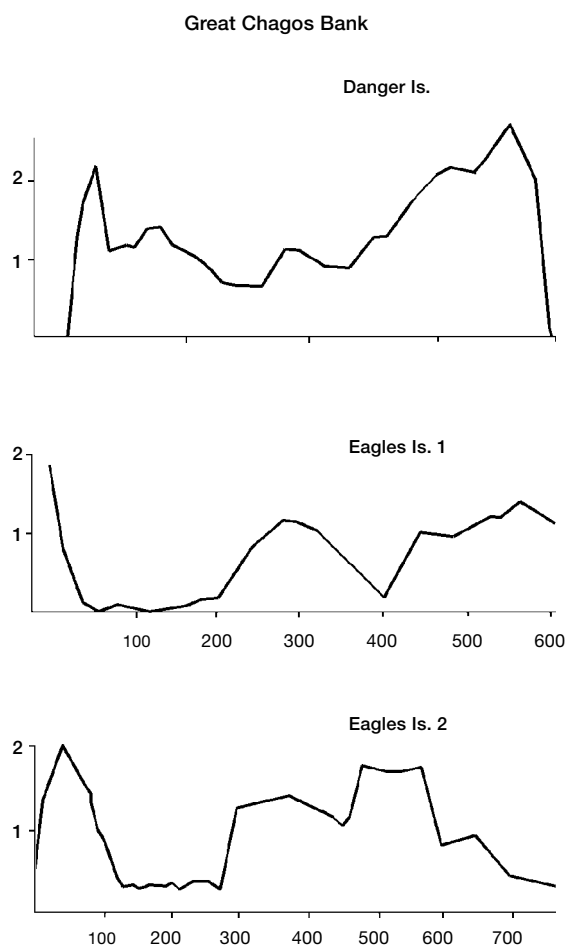


Figure 6. Profiles of islands of the Great Chagos Bank drawn for survey transects carried out in 1975. Numbers are all metres. Redrawn from Baldwin (1975).

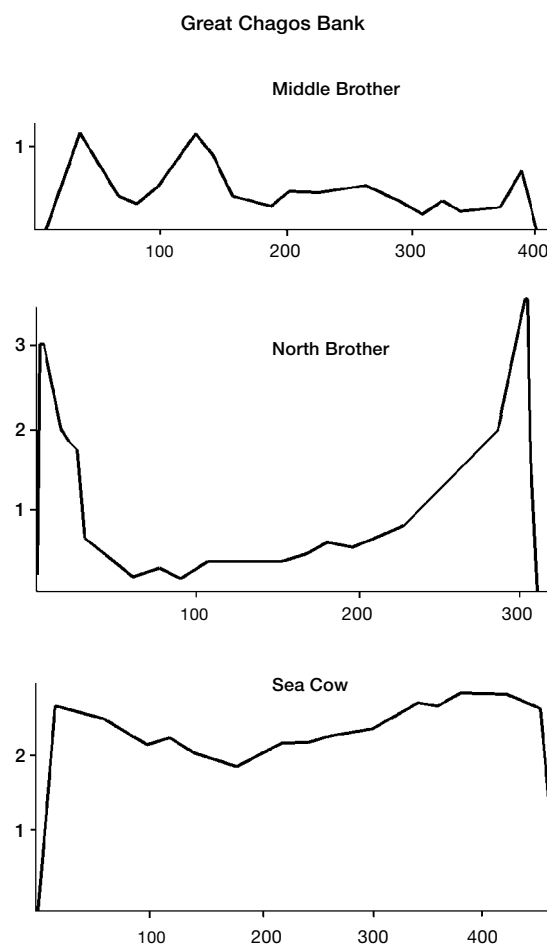


Figure 7. Profiles of islands of the Great Chagos Bank drawn for survey transects carried out in 1975. Numbers are all metres. Redrawn from Baldwin (1975).



Figure 8. North Brother island whose small but impressive cliffs are raised reefs. Note the profile of this island in Figure 7.

pressions extend variously over a small portion to most of an island. On some (e.g. North Brother, Fig. 8) the effect is almost of a thin shell surrounding a fertile and vegetated centre, while on others (e.g. the similarly sized island Sea Cow) the depression is small and the entire island is well above sea level. The largest islands measured in this way are those of Egmont atoll (Fig. 5) and Eagle Island (Fig. 6), both previously inhabited when copra was a valuable product. During and after heavy rain, freshwater 'lakes' may form in the interior of these islands, which seep gradually away over a few hours. Such is the flow of water that after episodes of rain, elevated nutrient levels may be detected offshore (Rayner & Drew, 1984). Given these island profiles it is likely that these nutrients accompany seepage through the very porous limestone rock rather than surface run-off. This high porosity is confirmed by the fact that disused wells located well inland in these Chagos islands show tidally linked rises and falls in fresh water level (Baldwin, 1975; Griffiths, 1979; Hunt, 1997).

Similar depressions are clearly visible in many islands in the two northern atolls. Commonly the effect may be visually exaggerated due to piling up of sand around the rims of islands, but in most cases coral rock visibly outcrops around the rims, and it is predicted that pro-

files are similar. Two sites in western Peros Banhos atoll appear to see this process taken much further: In Ile Monpatre and Ile Diamant, tidal channels split each island into two along their long axes, i.e. parallel with the atoll rim, leaving separate 'seaward-side' and 'lagoon-side' islands.

DISCUSSION

Most work following the coral mortality of 1998 has focussed on sublittoral reef conditions. Little so far has been done on researching consequences of reef mortality to biodiversity or to fisheries productivity, and even less has been done on the possible consequences of this mortality and sea level rise to shorelines and to islands hitherto protected by the reefs. Indeed, shoreline protection is traditionally seen as an engineering problem rather than one for biologists to worry about!

The effects of mortality, its possible recurrence, and sea level rise will clearly compound each other to a considerable degree. SST is trending upwards, so the strong possibility exists of repeat occurrences of coral mortality. Trends of sea level rise are likewise upwards (IPCC, 2001), further increasing clearance between wave crests and reef substrate. Rising sea level means increasing depth of water above the reef flat, which thus becomes decreasingly able to attenuate wave energy. The loss of shallow corals to seaward of the reef flat decreases the capacity for wave attenuation before the reef flat is reached. There is no good data on the condition of the reef crest, but incidental observations (Sheppard, 1999c) suggested that cover by red algae in such areas was reduced by about half following 1998. At present, therefore, it appears likely that all three natural 'lines of defence' are being reduced.

Two consequences are likely. First is erosion of the elevated rims of islands. This was observed to be taking place in one or two areas which are well known to this author, though no measurements have yet been taken. If erosion progresses, clearly breaching of the rim could occur, which would lead to sea water flooding of the central portion of the island. Fig. 9 shows erosion of the



Figure 9. Eroded rim of the island of Ile de Coin, Peros Banhos atoll. Vertical height of the eroded 'cliff', from vegetation at top to sand at foot, is nearly 1 metre.

rim of one such Chagos island on Peros Banhos atoll, inhabited until the mid 1970s. This erosion certainly took place since that time (personal observations). Fig. 10 illustrates the results of flooding of depressions in two Chagos islands; in one case a breach is also visible. It is not necessarily suggested that this is a consequence of recent sea level rise, but it illustrates the effect.

Secondly, rainfall on these islands is between 2,500 and 4,000 mm y^{-1} (Topp & Sheppard, 1999), which is the highest of any Indian Ocean archipelago. It may be presumed that the concave surfaces of these islands retain most of the rain water, which then percolates into the rock, with very little being lost by lateral surface run-off. Because of this and the high fresh water input, all larger islands maintain a fresh water lens, which in turn supports vigorous vegetation and, in past times, a human population. Small water lenses can be maintained only when sufficient fresh water falling on the island can maintain a pressure, or flow, outwards through the porous rock to a degree which exceeds inward pressure from sea water. A rising sea level will increase the inward pressure of sea water, potentially compromising the fresh water interior. This appears likely even if there is no breach of the raised island rim. These islands include both remarkable remnants of native Indian Ocean island hardwood



Figure 10. *Top.* Flooded depression in Ile Anglais, Salomon atoll. *Bottom.* Small islet in Diego Garcia atoll, illustrating a breach of island rim and ingress of sea.

(Topp & Sheppard, 1999) and very important populations of sea birds (Symens, 1999) as well as recovering populations of species such as turtles (Mortimer & Day, 1999), all of which are likely to be threatened by a sea level rise much smaller than that needed to completely cover the islands.

It might be suggested that reefs can simply grow upwards to match a rising sea level. After all, colony extension rates of most coral species exceed the rate of sea level rise. However, reef growth and coral colony growth are not the same thing, though they have been commonly confused, and reef growth in atolls has long been known to be only 0.2 to 3 mm y^{-1} , much slower than rates of extension of coral colonies (e.g. Hopley, 1982). Formation of durable reef substrate such as that of which a reef flat is made, as contrasted with simple growth of coral colonies, is a complex and poorly understood issue, and indeed, reef growth and coral growth

even become 'uncoupled' in many situations where conditions are sub-optimal (Sheppard *et al.*, 1992). In the Chagos archipelago there are as many reefs and 'drowned atolls' which failed to reach present sea level as there are islanded atolls, even though the last several thousand years has showed no significant sea level change. We can, unfortunately, have little hope that reefs will keep up with a sea level rise of the magnitude currently being predicted over the next 20 years and longer. This means there will be an increasing height of water above the reef flats, with corresponding reduction in the ability of reef flats to attenuate wave energy.

Although new coral recruitment is high, over the next few years and decades it is likely that coral mortality events will recur. The projected temperature trends illustrate the point (IPCC, 2001). SST in April 2001 reached to about 0.5°C of the very damaging 1998 value. This being the case, the fine balance between reef growth and erosion could worsen, and there may be more widespread problems of erosion throughout the archipelago. Even if artificial means such as breakwaters could be developed to resist breaching of island rims without creating damage to other aspects of these ecosystems, the worry remains that increased inwards pressure from rising sea levels will increase. This could threaten the island interiors, their freshwater lenses and the biota supported by them.

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